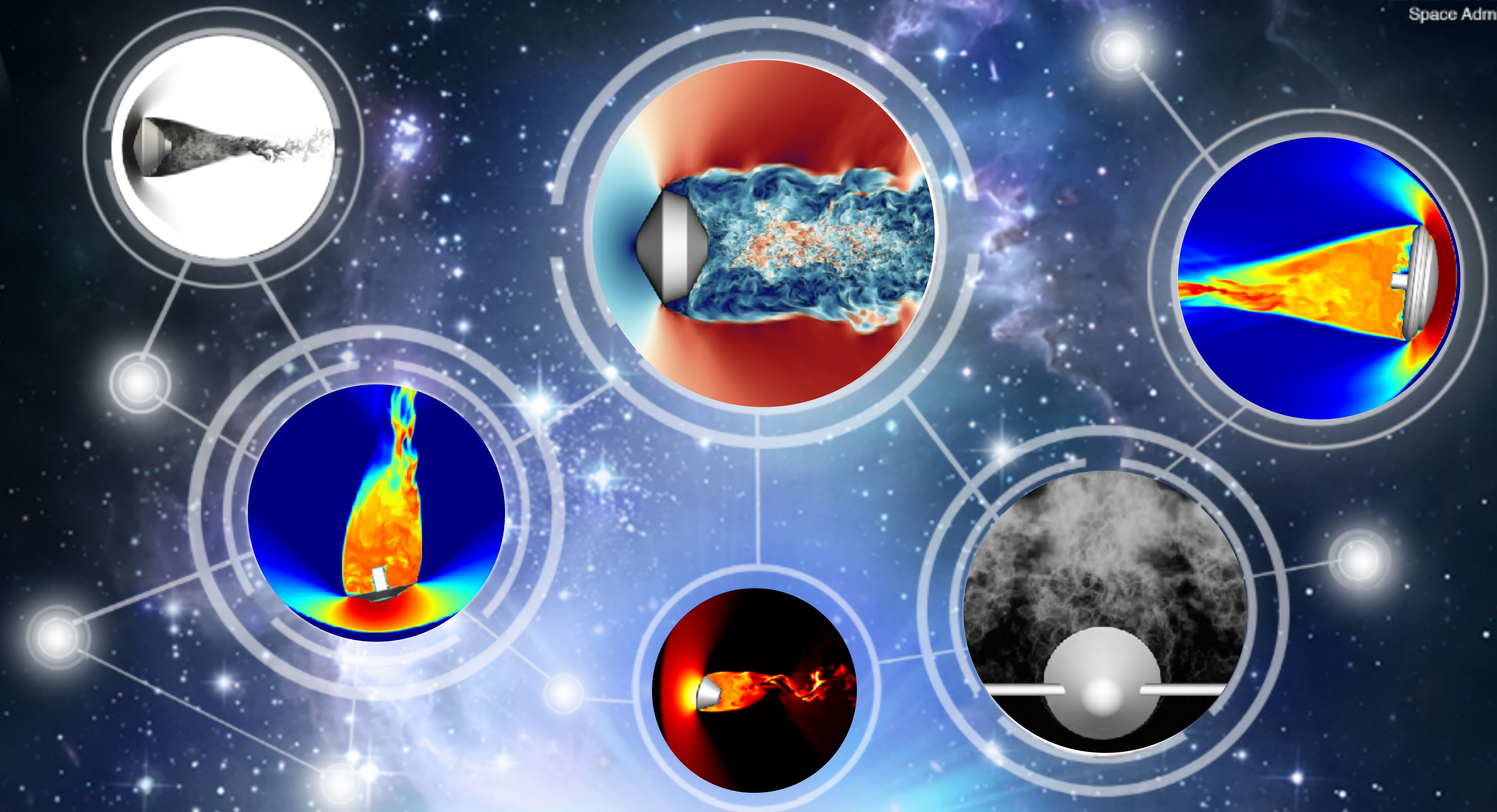


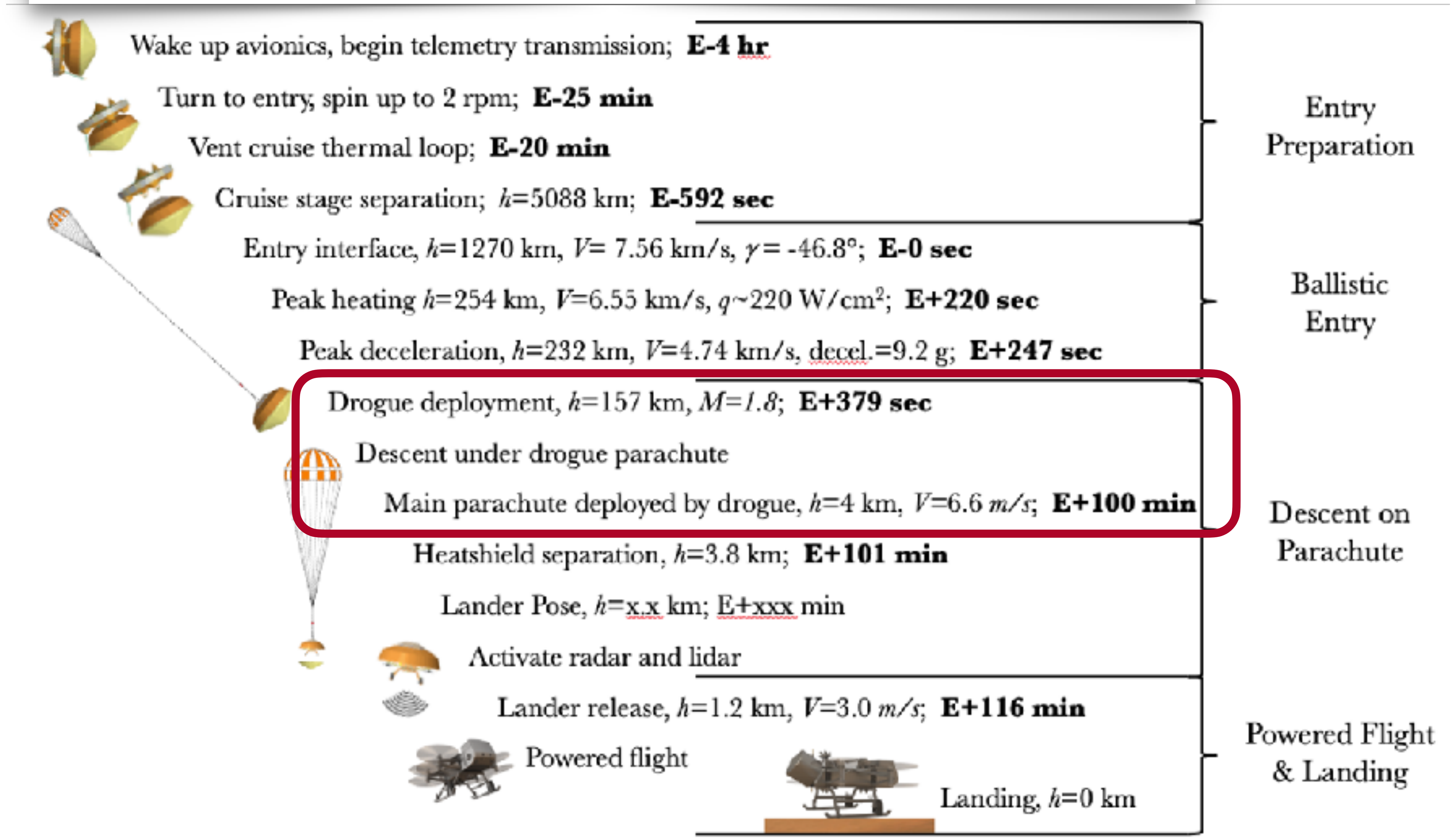
DYNAMIC STABILITY CHARACTERIZATION USING FREE-FLIGHT CFD

Joseph Brock
Eric Stern
Cole Kazemba
Quincy McKown
Dirk Ekelschot

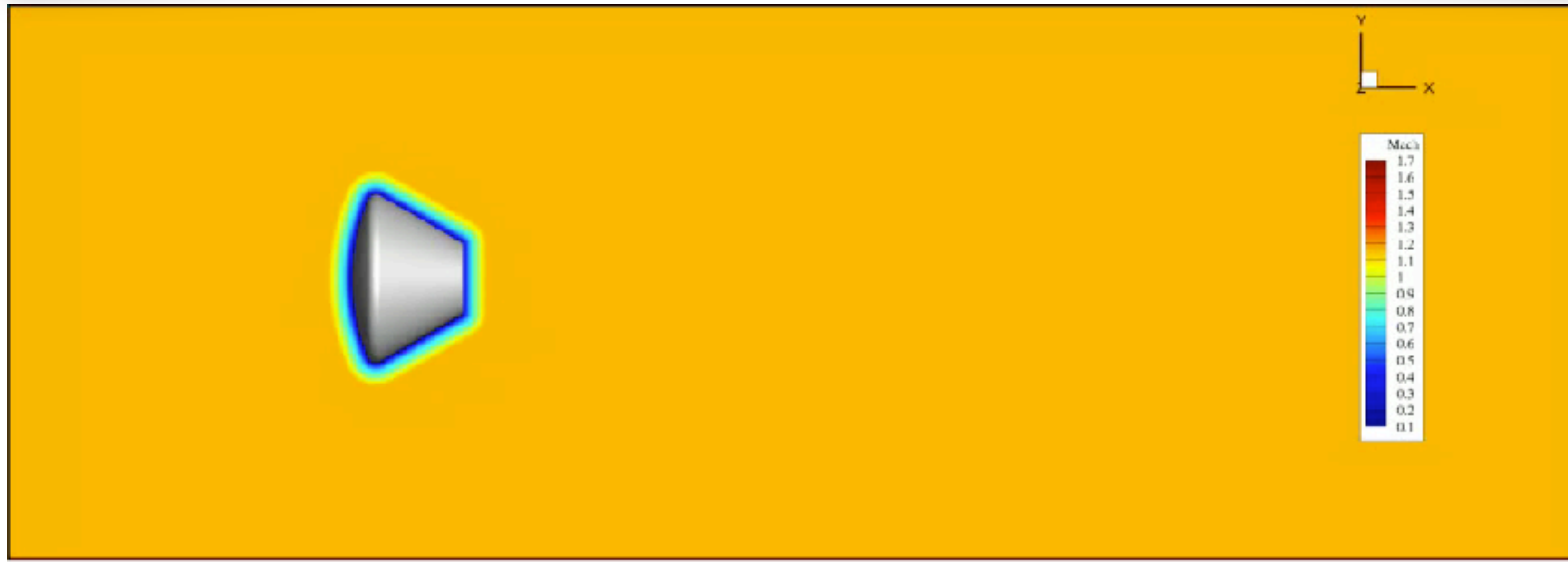
Dynamic Stability and FFCFD

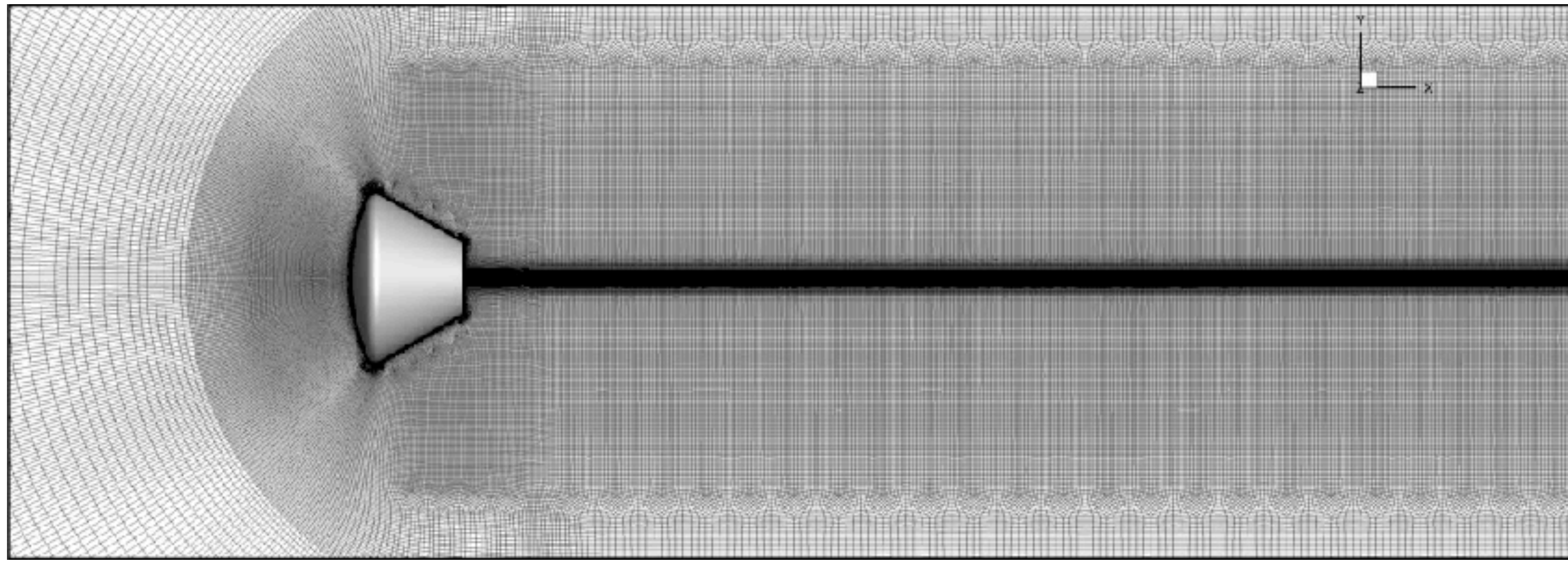
Genesis Sample Return Capsule (Desai, 2008)

Dynamic instabilities of blunt bodies often arise at low-supersonic and transonic Mach numbers



- CFD is an integral part of *static* aerodynamic characterization and design.
- Would be desirable to have similar capability for *dynamic* aerodynamics

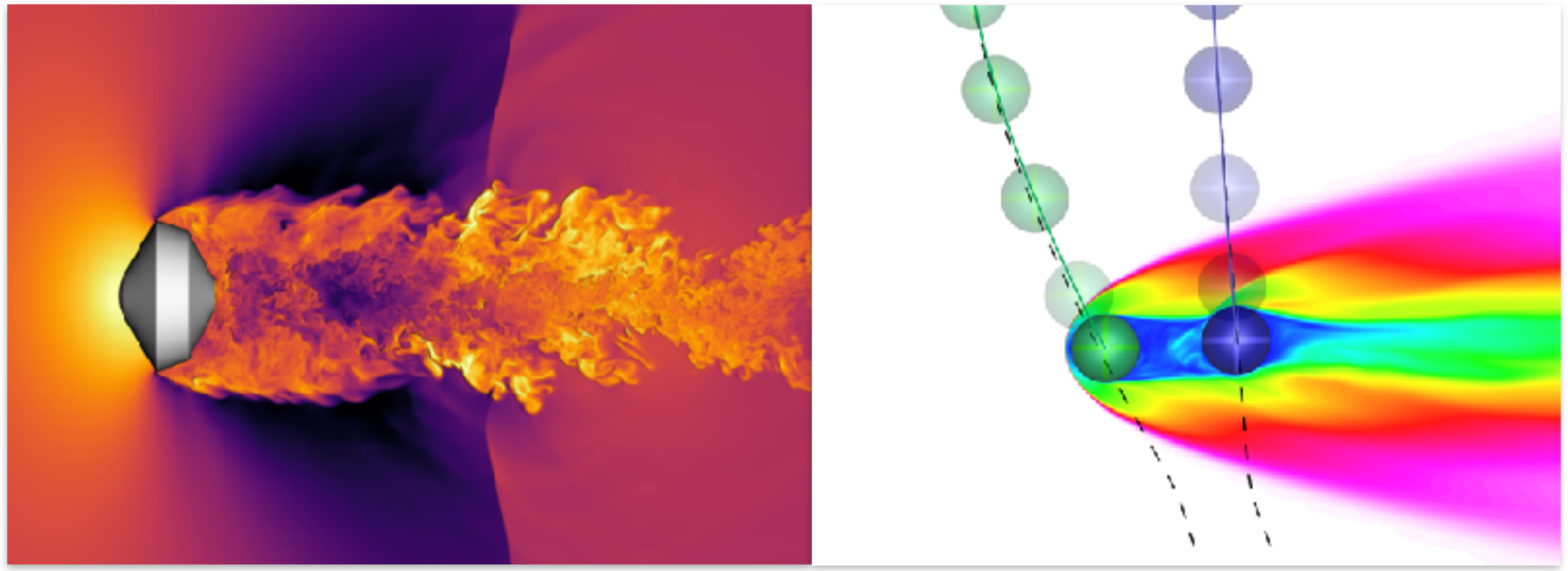


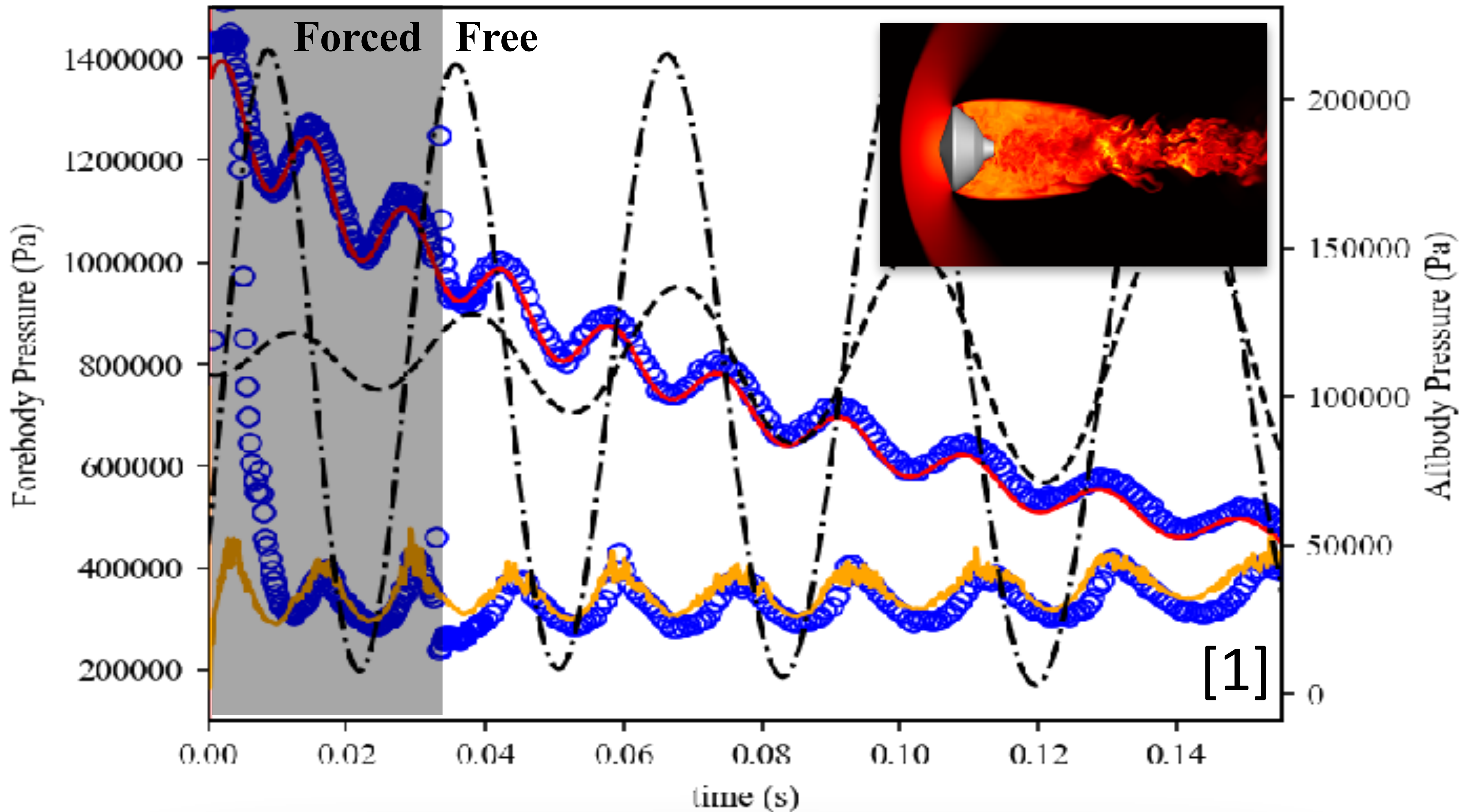


Free-Flight CFD (FFCFD) combines a mesh deformation capability into an existing CFD solver (US3D) to allow an object to rigidly rotate about a center-of-gravity in response to aerodynamic forces. Translational velocities, which are accounted for in the discrete equations, allow a full six degrees of freedom simulation of free-flying objects.

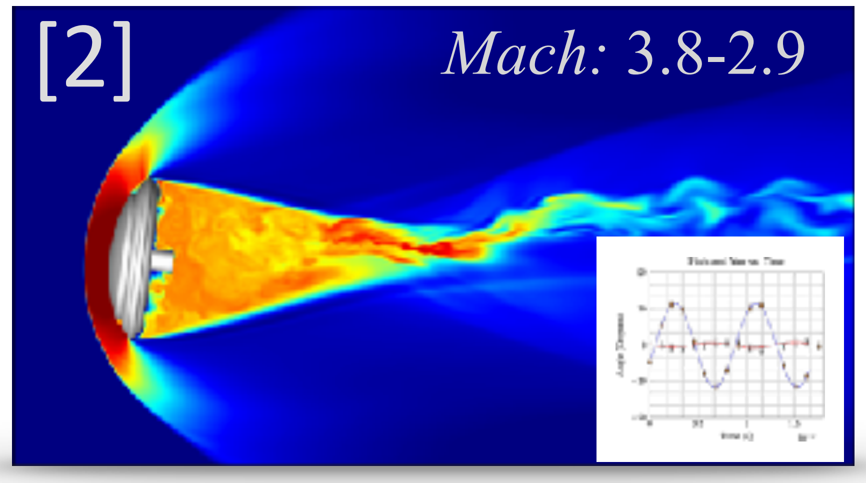
Current State of the Art

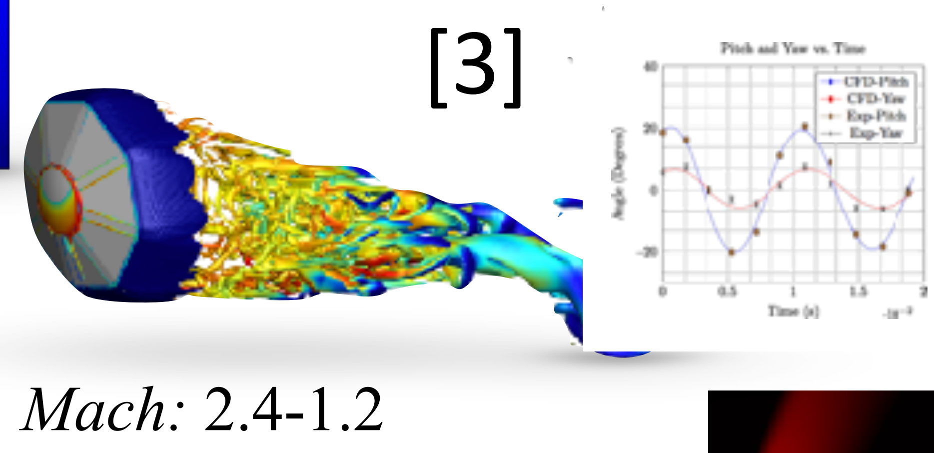
Single/Multi-body Dynamics

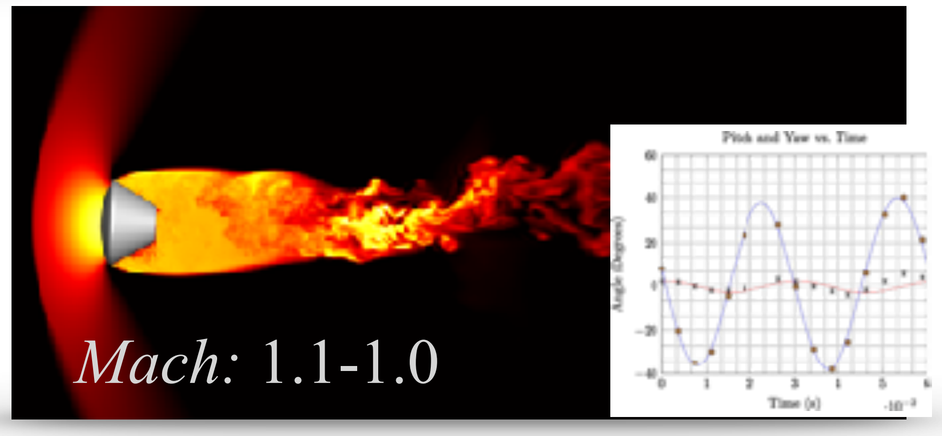




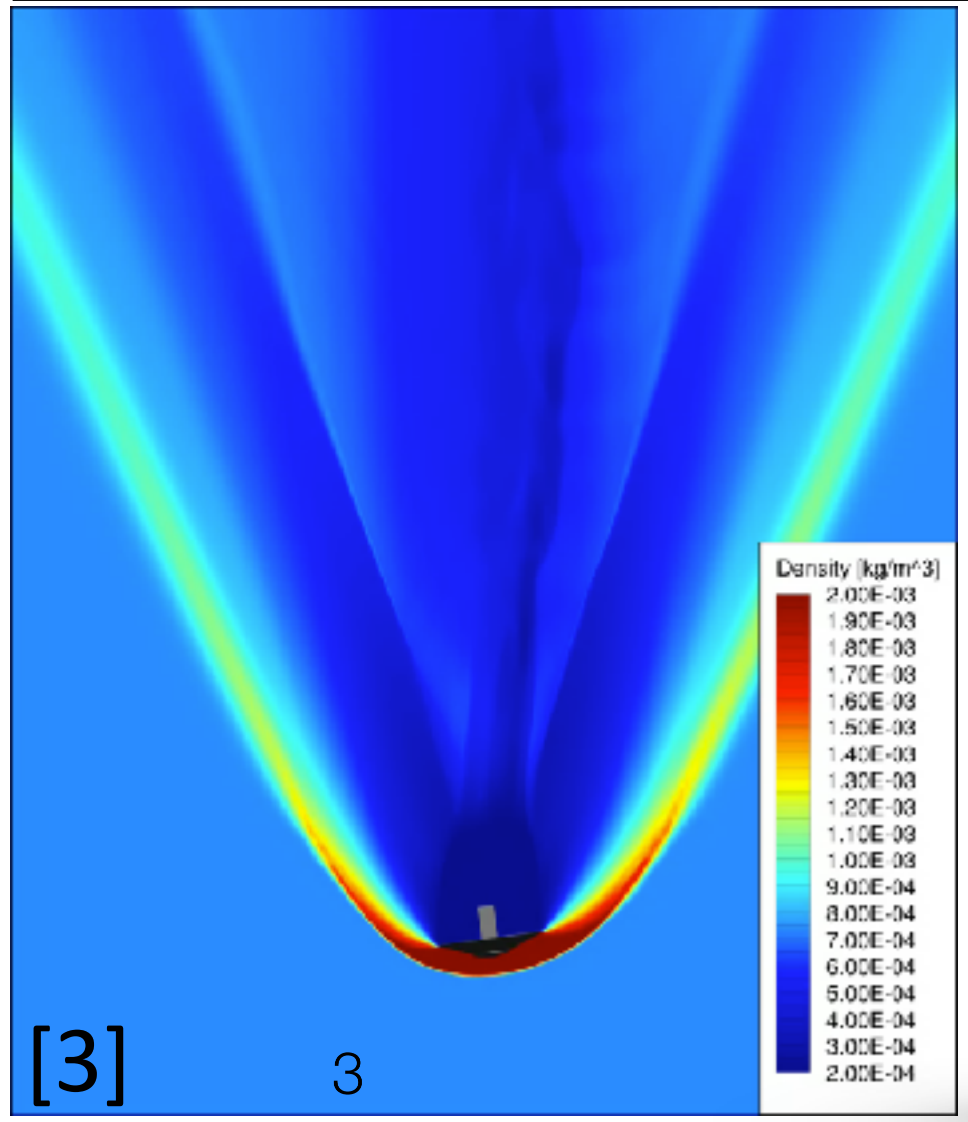
Validated against Experiment

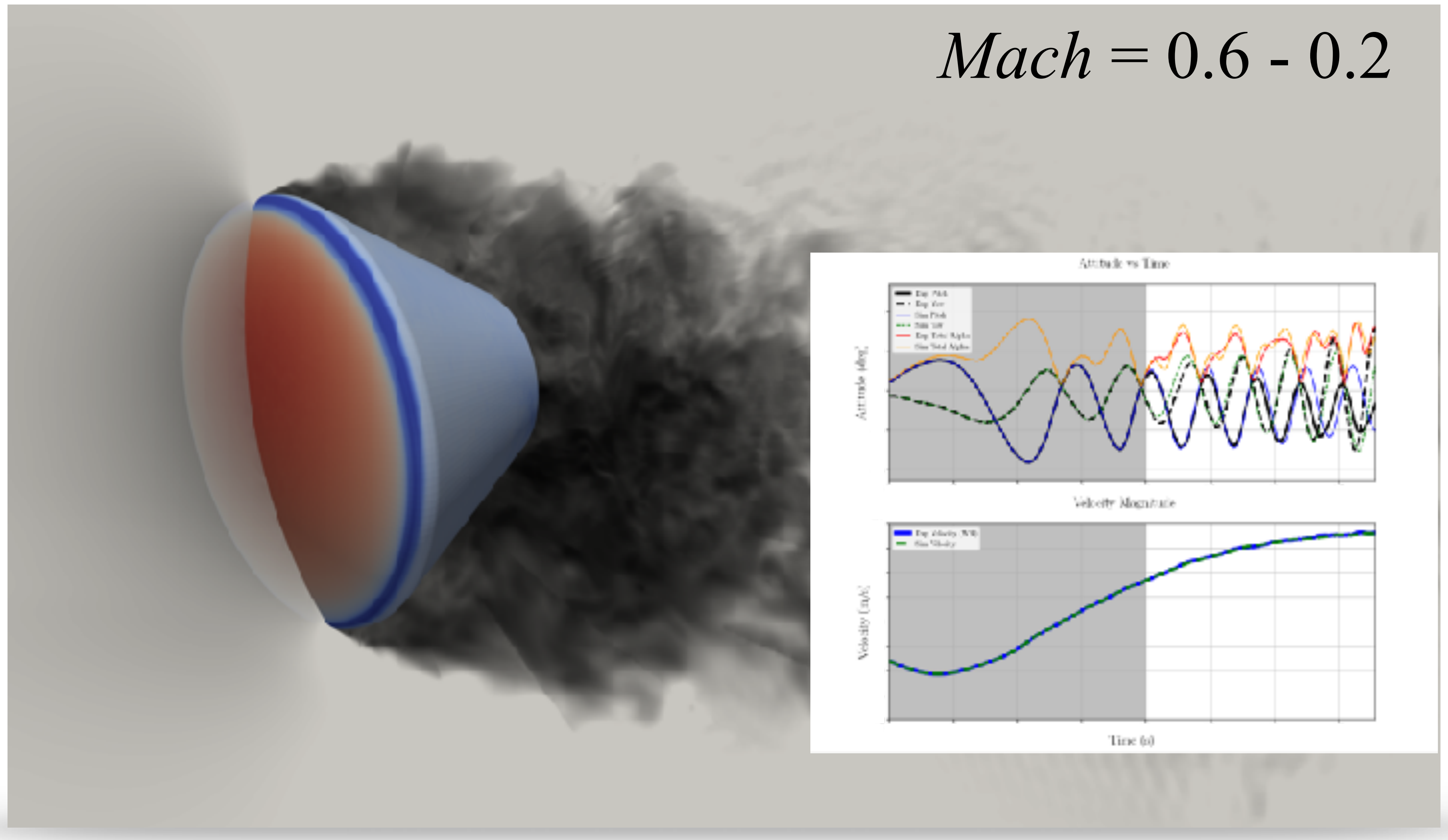




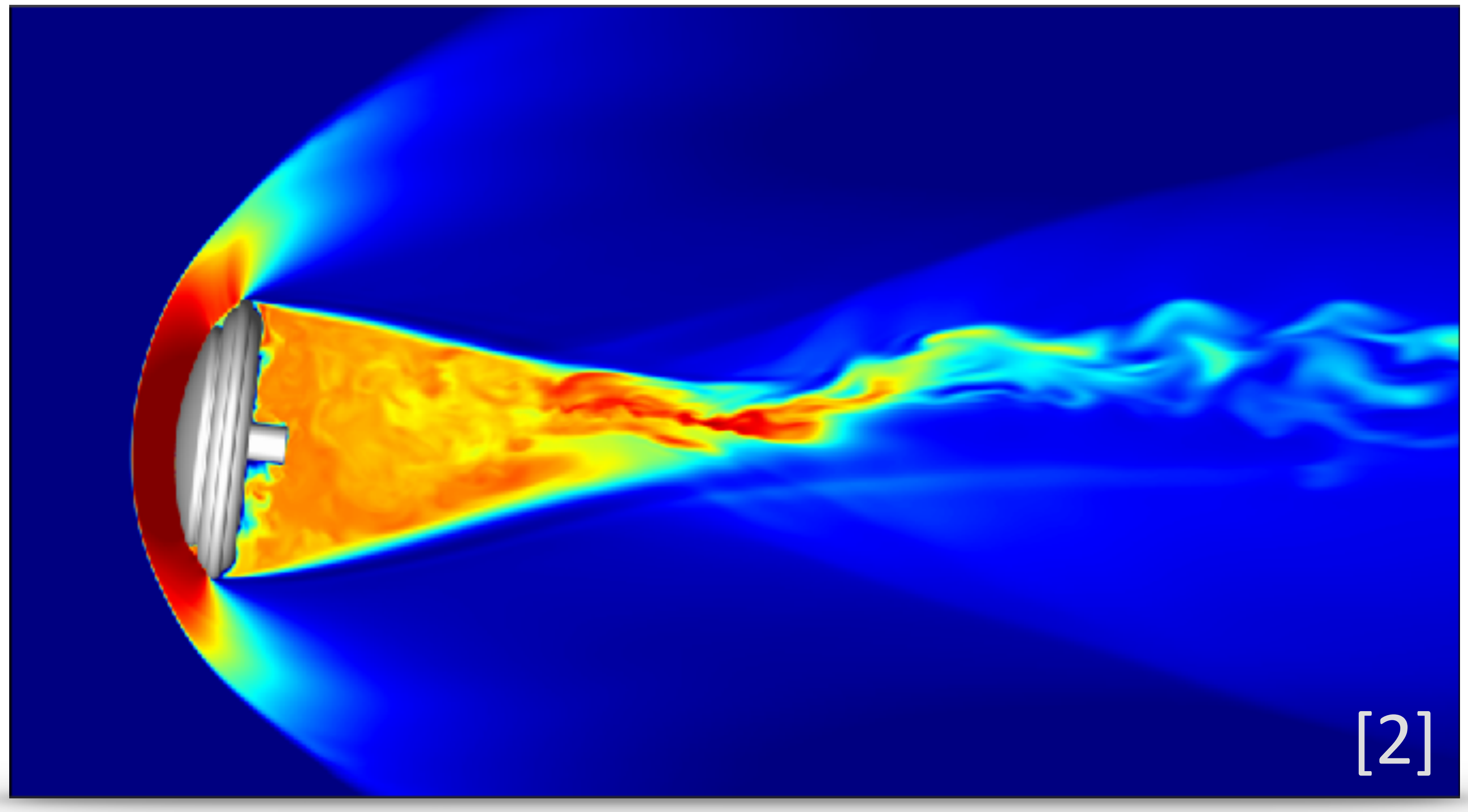


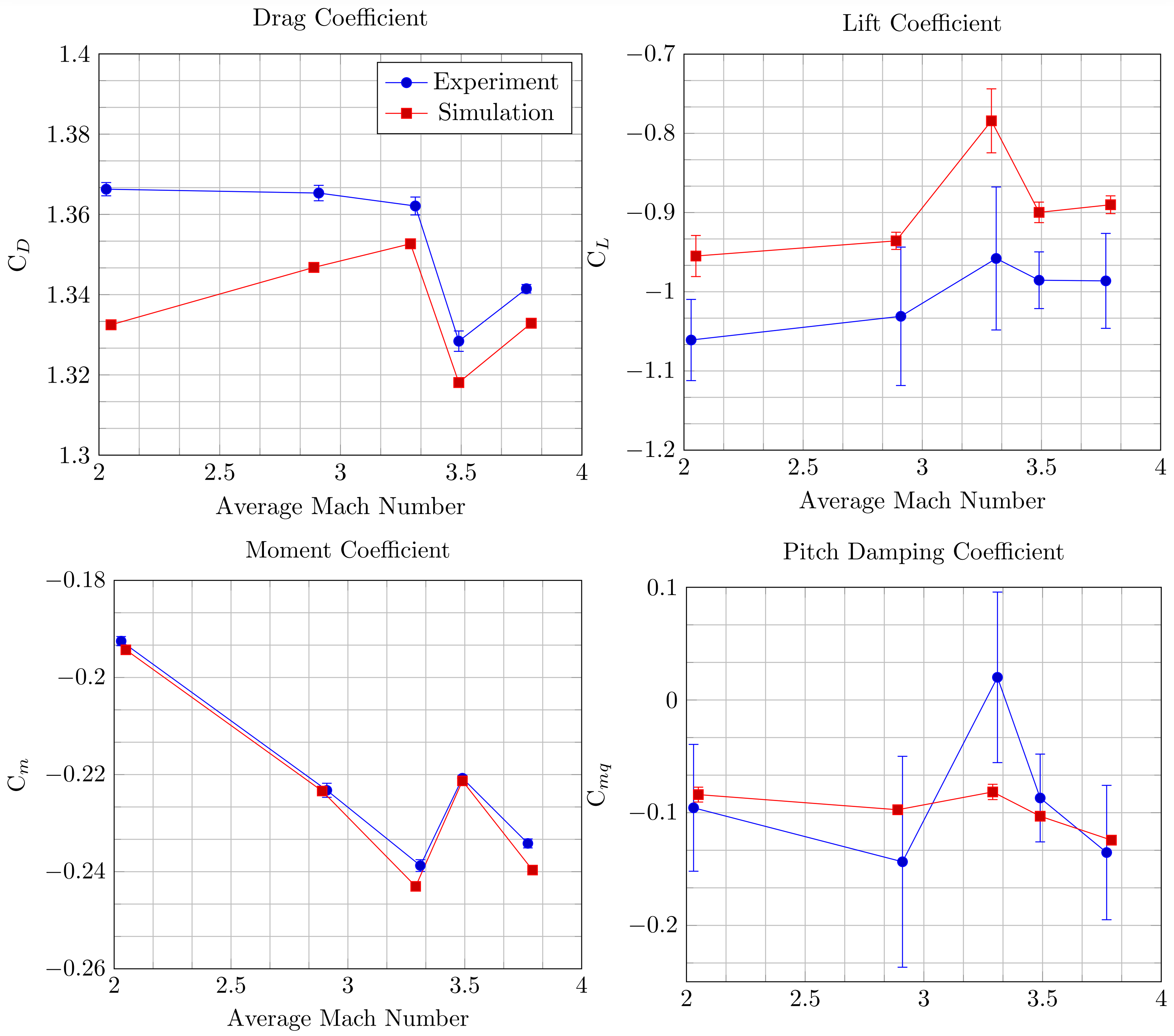
Atmospheric Flight with EarthGRAM





Free-Flight CFD Data as Input to Heritage Methods

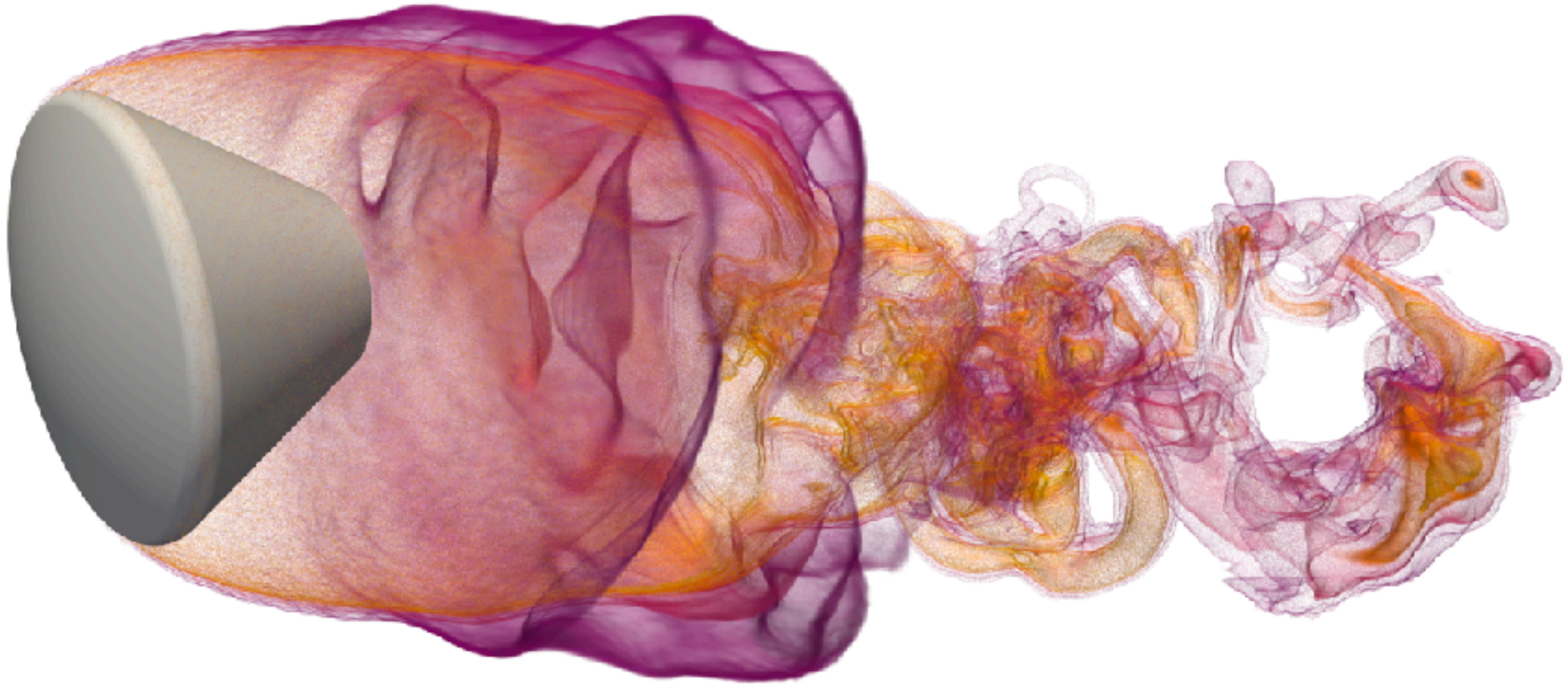




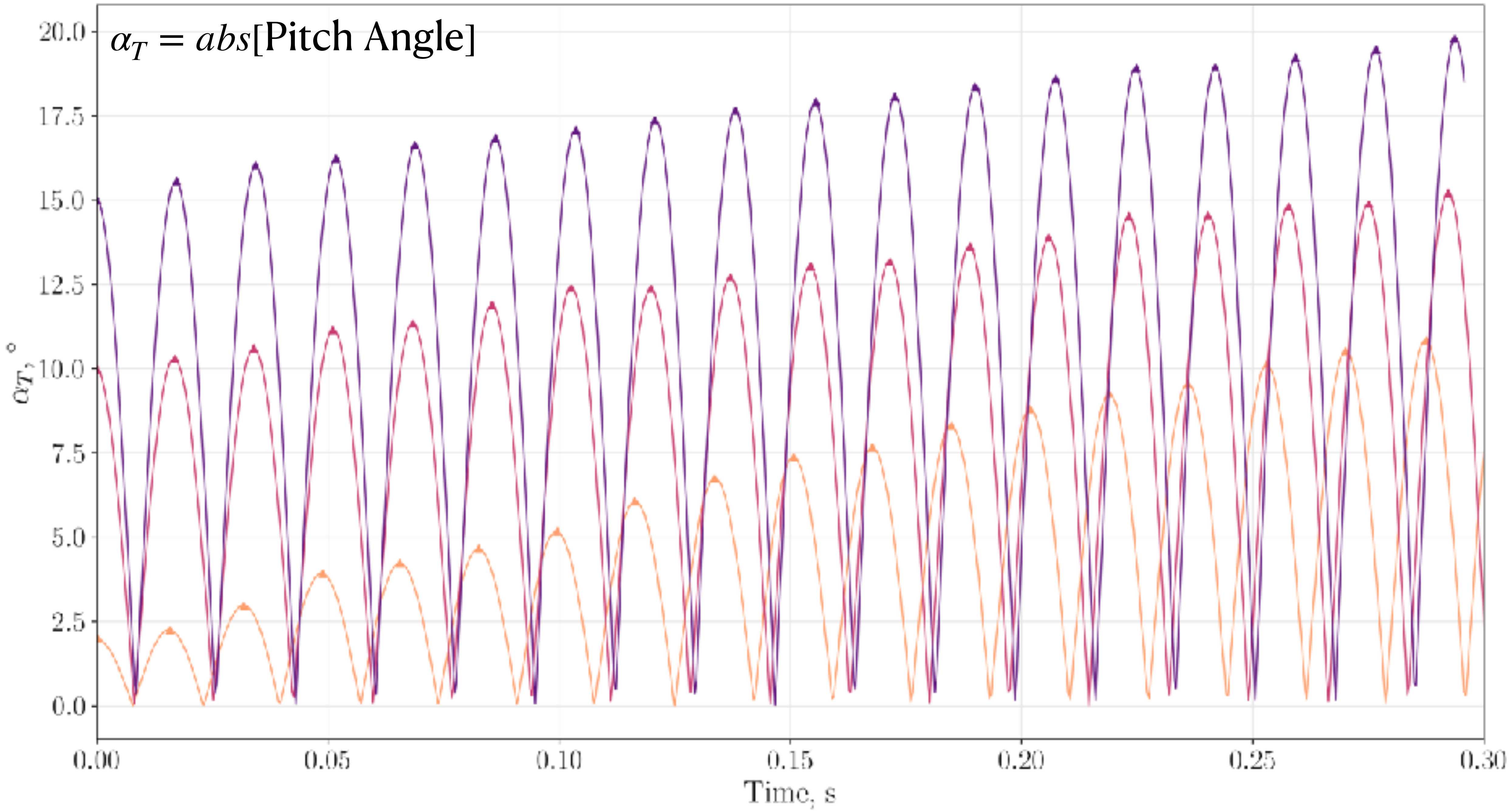
- Dynamic stability is often characterized by the pitch damping coefficient C_{m_q}
- Derivations of pitch damping coefficient in previous studies were obtained using the aerodynamic software CADRA
  - Results shows good comparison between simulation and ballistic range results
  - Required significant coarsening from order 100,000 time steps of CFD data down to 16 data points to obtain 1-to-1 comparison with BR data
- Rich datasets from FFCFD simulations present an opportunity to apply new data reduction approaches

Improved Data Reduction for Free-Flight CFD

- **PYnamics software suite to post-process FF-CFD output**
  - A python based suite of tools available to post-process FFCFD data and generate static and dynamic aero-coefficients
- **Schoenenberger [5] states that (within assumptions of derived models) an equivalent CMq can be derived from 1- 2- or 3-DoF simulations**

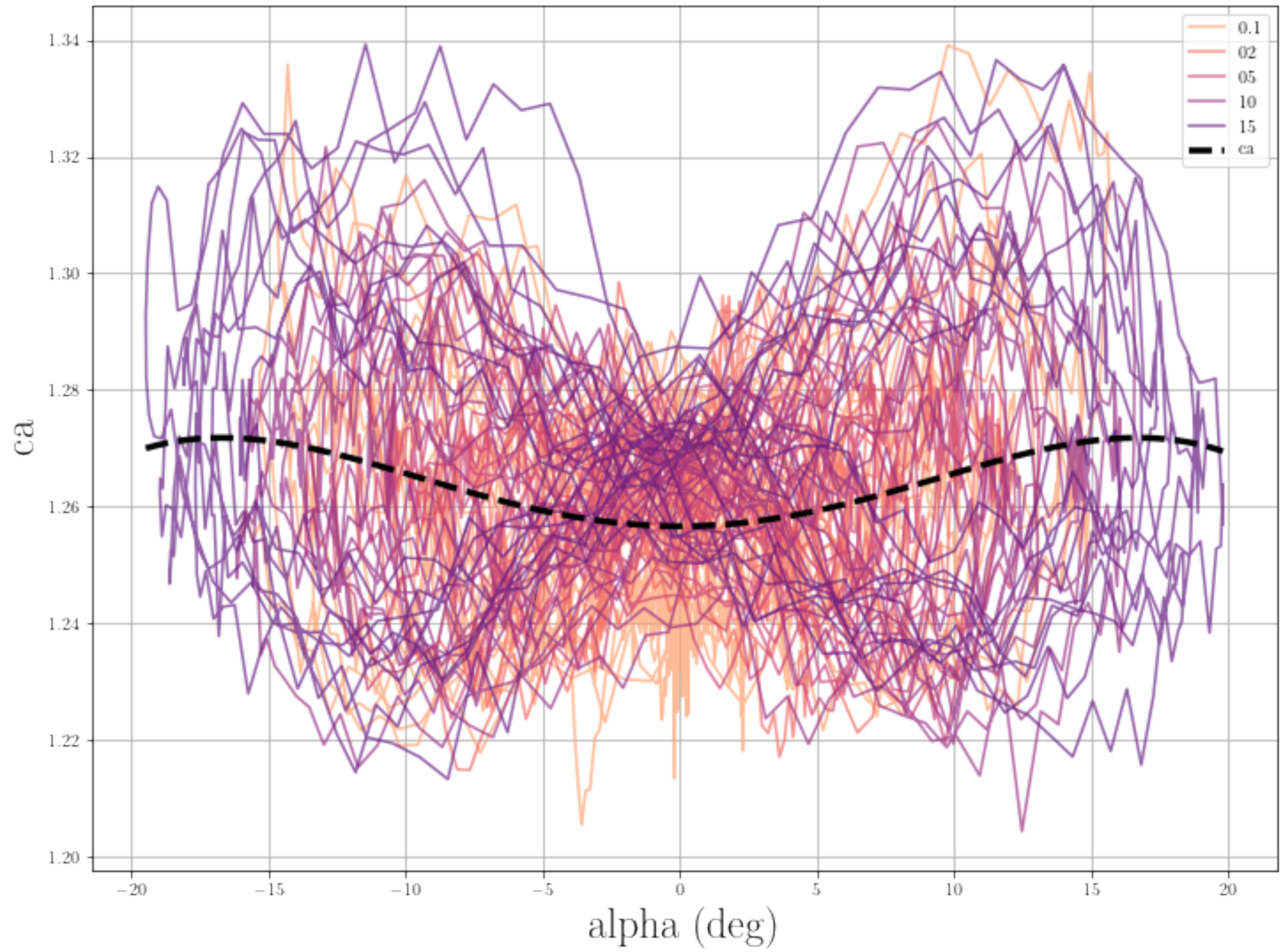


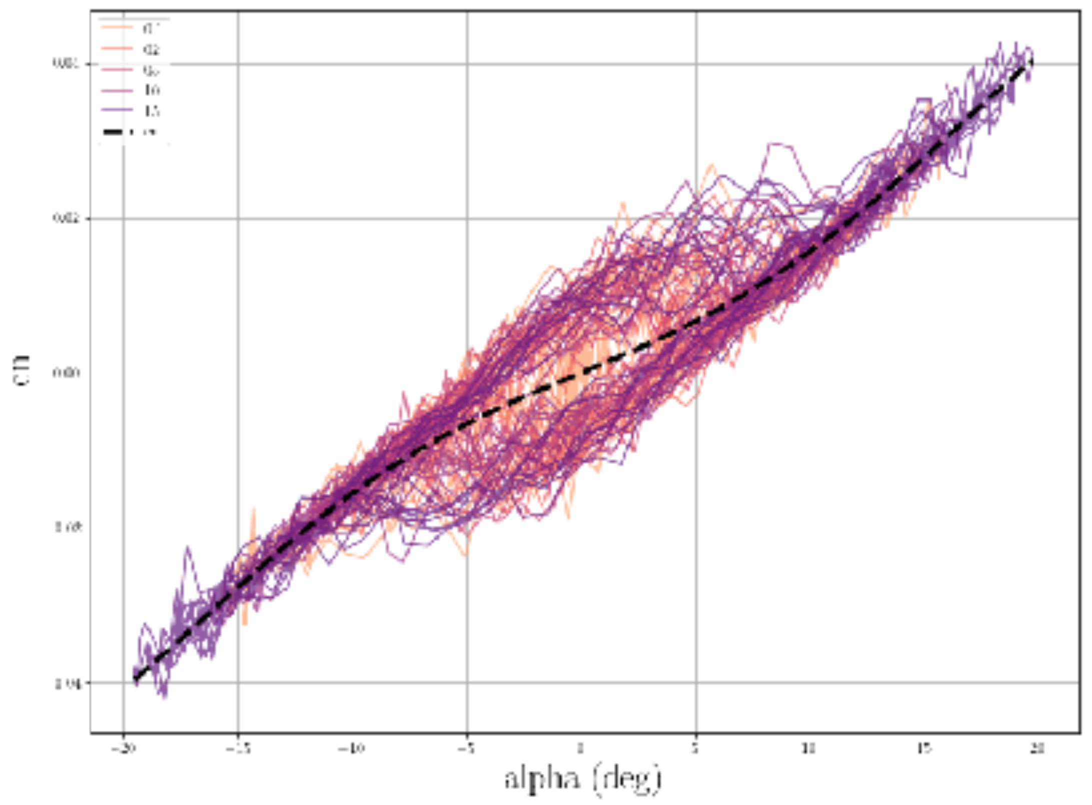
- **Methodology for using FF-CFD 1-DoF analysis to computing dynamic coefficients**
  - Simplified approach to FF-CFD simulations using reduced degree-of-freedom simulations accompanied by analytical forms of dynamics equations allow deeper understanding of free-flight dynamics as well as generate non-linear pitch damping fits using a range of data reduction methods

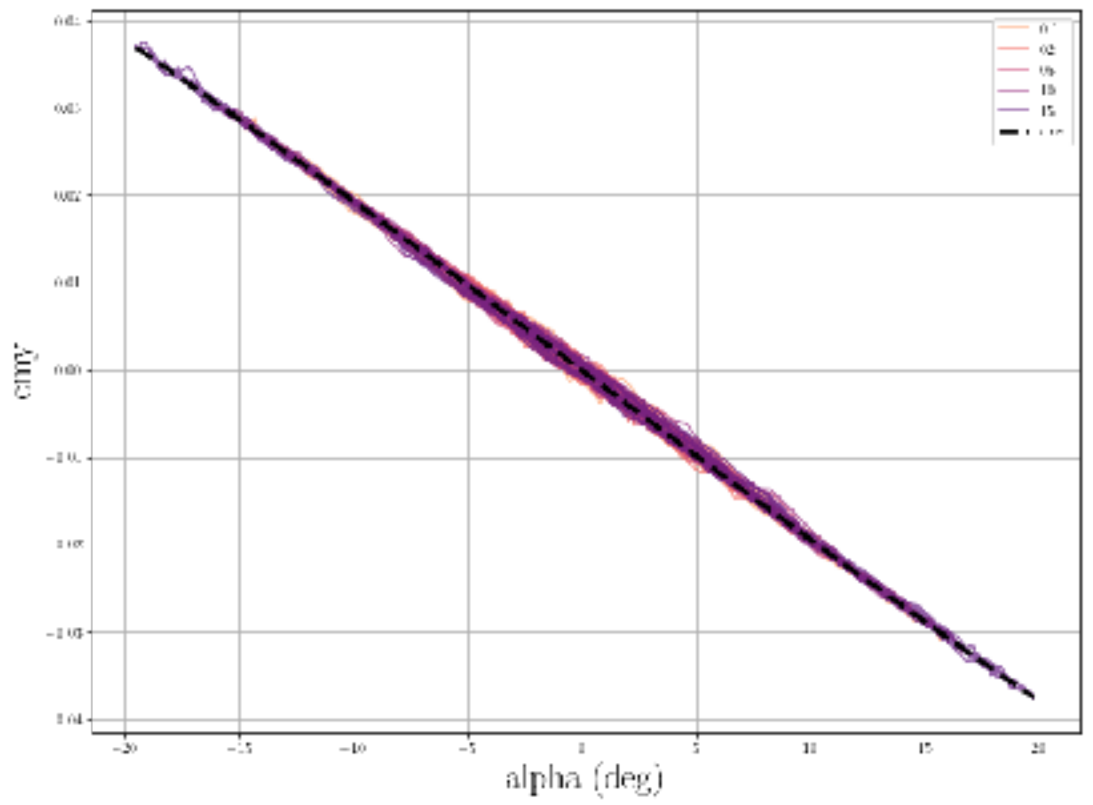


Static Aero Derived from Dynamic Simulations

- Functional form fits are derived from ARFDAS BR model
  - C_N and $C_M = C_1 \sin\alpha + C_2 \sin\alpha^3 + C_2 \sin\alpha^5$
  - $C_A = C_0 + C_2 \sin\alpha^2 + C_2 \sin\alpha^4$
- Hysteresis exhibited in all static coefficients
  - Largest in axial force
  - Increase effect with larger amplitude of oscillation
- Static fit is applied to totality of 1-DoF trajectories: All amplitudes for all cycles
  - Fit is effectively weighted by oscillation amplitude
- Study was performed using only peak ($\dot{\alpha} = 0$)
  - Difference was $O\left(1\,\%\right)$







Dynamic Coefficients from FFCFD

- **Methodology for using FF-CFD 1-DoF analysis to compute dynamic coefficients [6]**
  - Simplified approach to FF-CFD simulations using reduced degree-of-freedom simulations accompanied by analytical forms of dynamics equations allow more densely populated Mach-alpha aero-databases

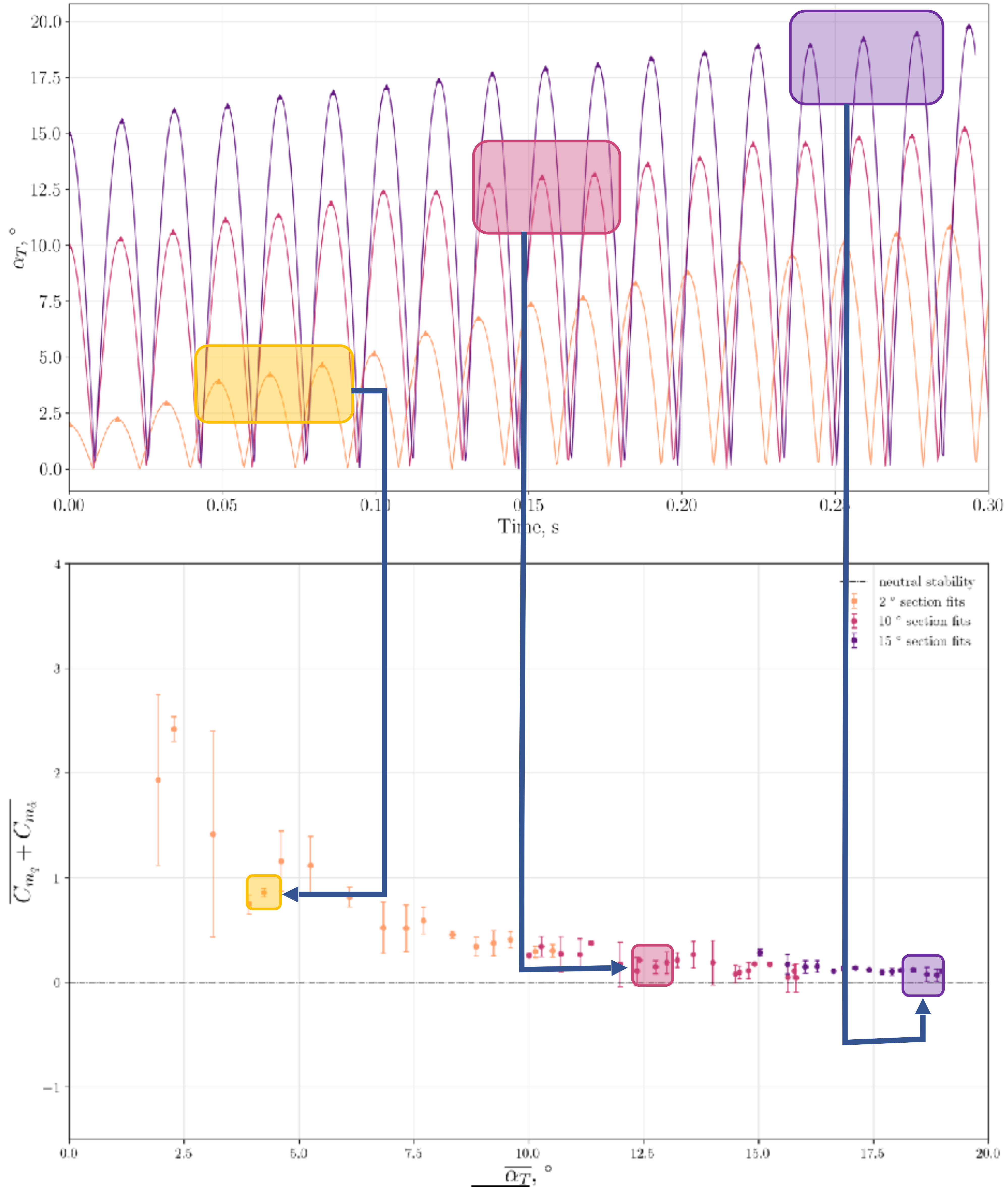
For each α_0:

- Using a stencil of 3-5 peaks, fit analytical expression for $\bar{C}_{m_q}$ to segments of the trajectory to capture local amplitude growth (or decay)
- Add this $\bar{C}_{m_q}$ value to our larger $\bar{C}_{m_q}$ vs a space at the average total angle of attack for the peaks within that stencil
- Move to next set of stenciled peaks and repeat

Combine all individual stencil fits into amplitude bins

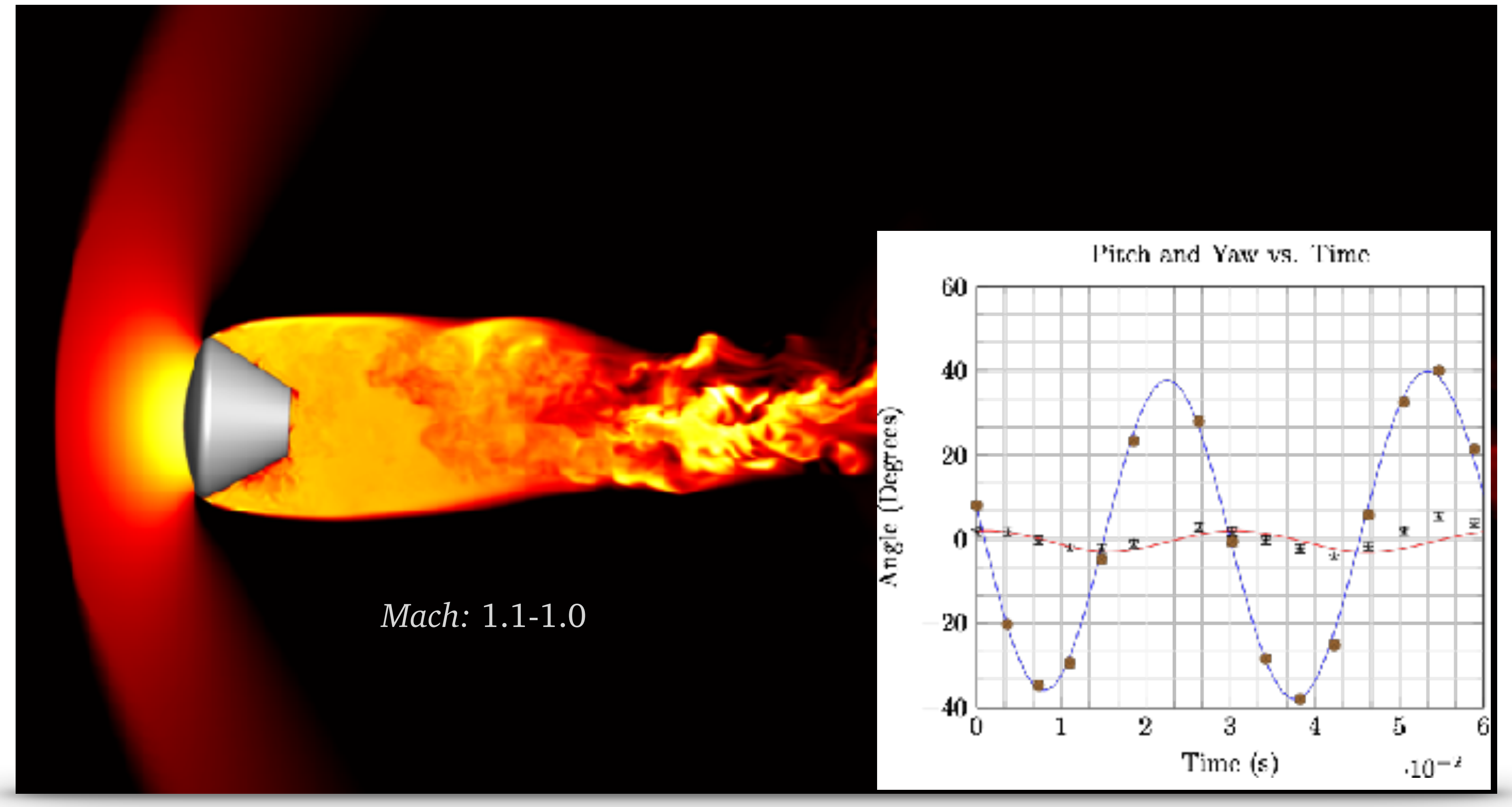
Curve fit bins to get $\bar{C}_{m_q}$ as a function of amplitude

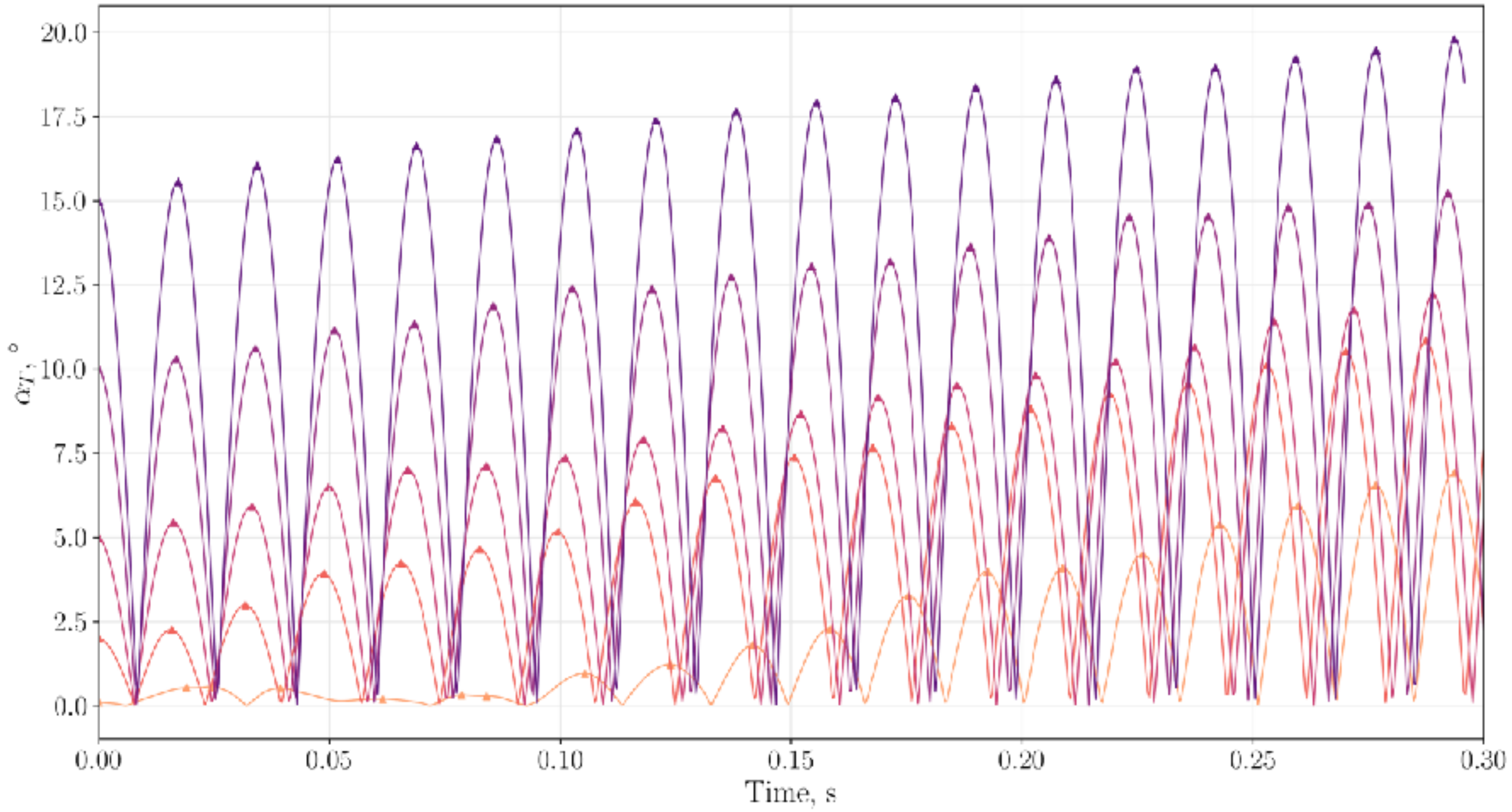
Results in a mapping across all ***amplitudes***

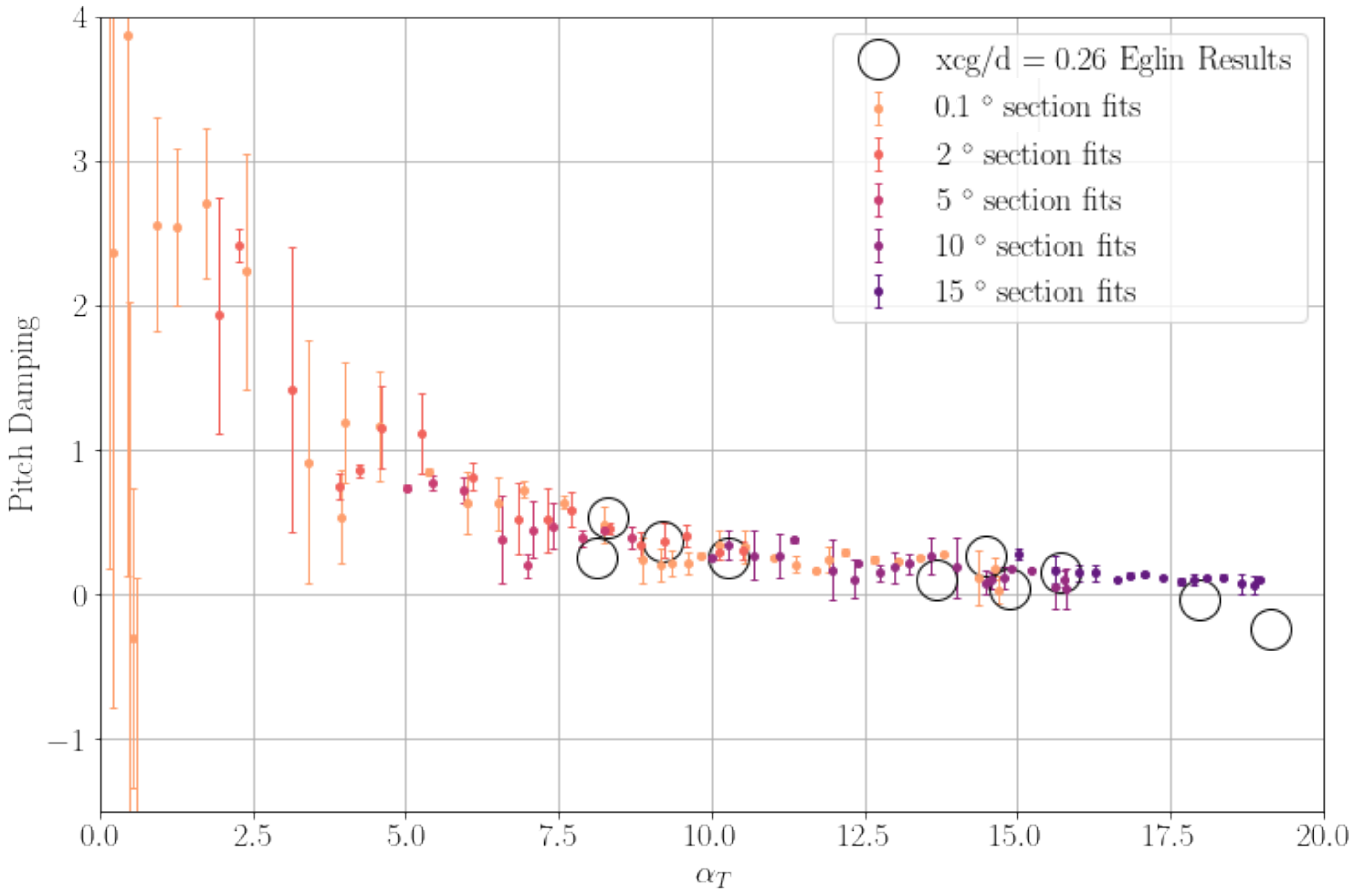


Comparison to Crew Module

- 1-DoF FFCFD dynamic analysis applied to Orion CM
  - Constant Mach=1.07 corresponding to mid Mach condition of HFFAF BR Shot 2366
- All initial amplitudes grow with no observable stable limit cycle
- Comparison of derived $\bar{C_{m_q}}$ distribution of section fits from 1-DoF trajectories agree well with experimental data obtained at a separate facility
  - Results suggest dynamic behavior is consistent between facilities and simulation



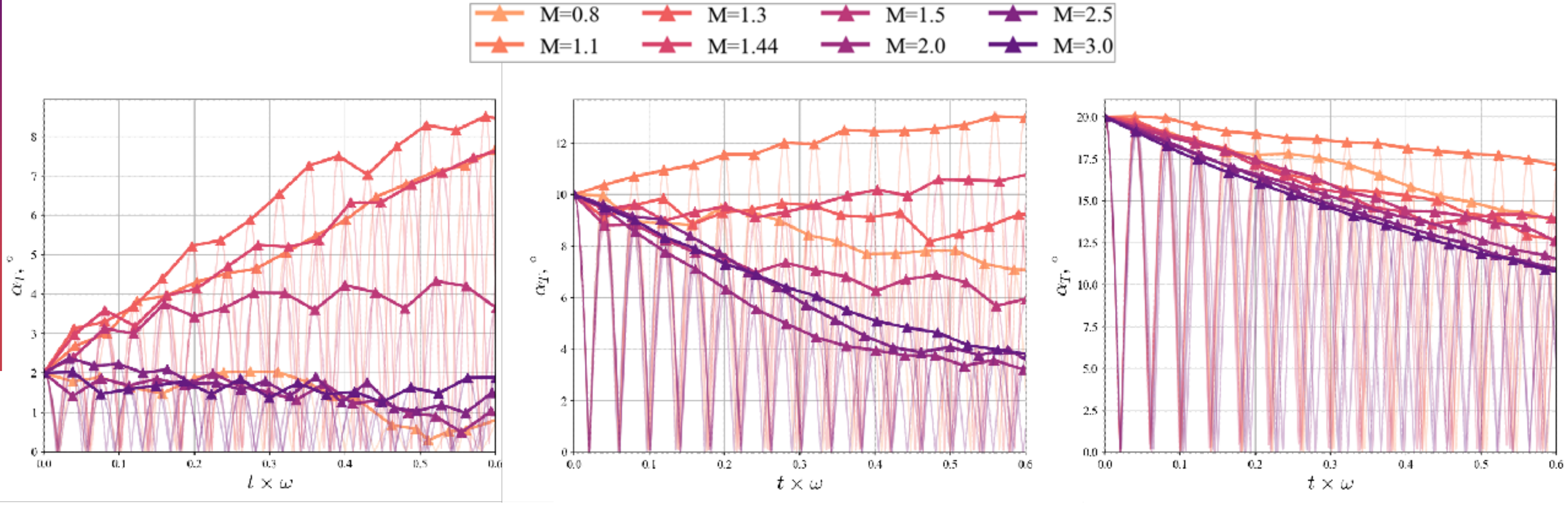




Application to DragonFly Mission

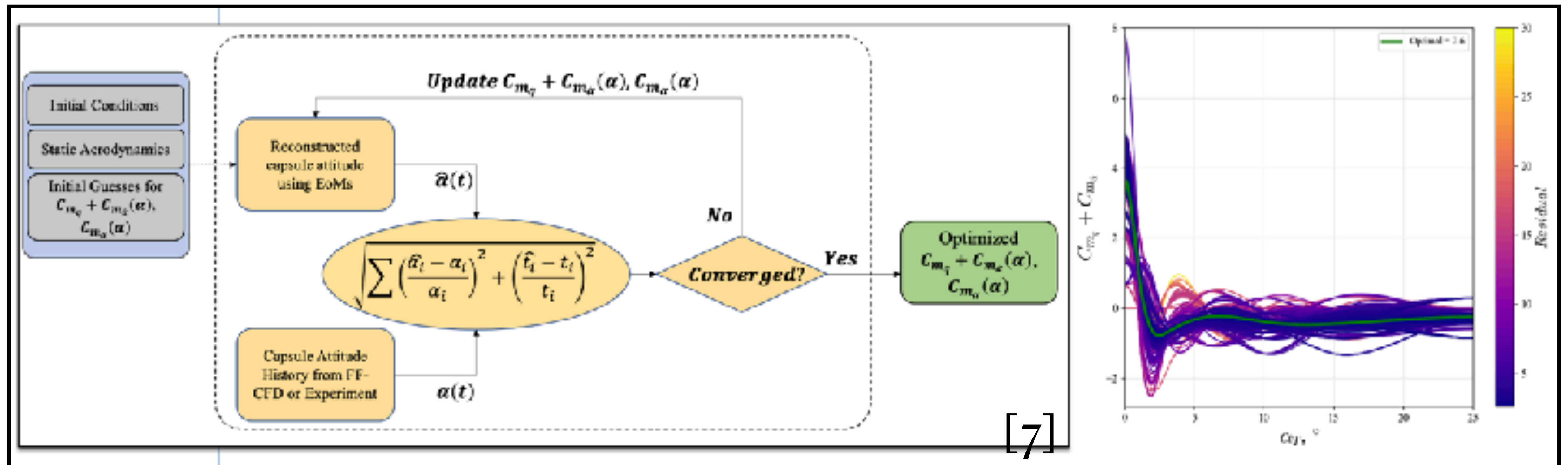

Centerline counters of Temperature

- The Dragonfly mission relies on free-flight for a significant portion of their EDL
  - >5 minutes of free-flight and ~100 minutes under drogue
- Transonic and subsonic aerodynamics remains a key challenge
  - **Heritage ADB remains coarse throughout this speed regime**
- FFCFD provides potential early assessment of vehicle behavior to aid in design choices
  - Population of Mach-alpha aero database for Genesis OML provides static and dynamic coefficients
    - Insight into aerodynamic behavior/characterization



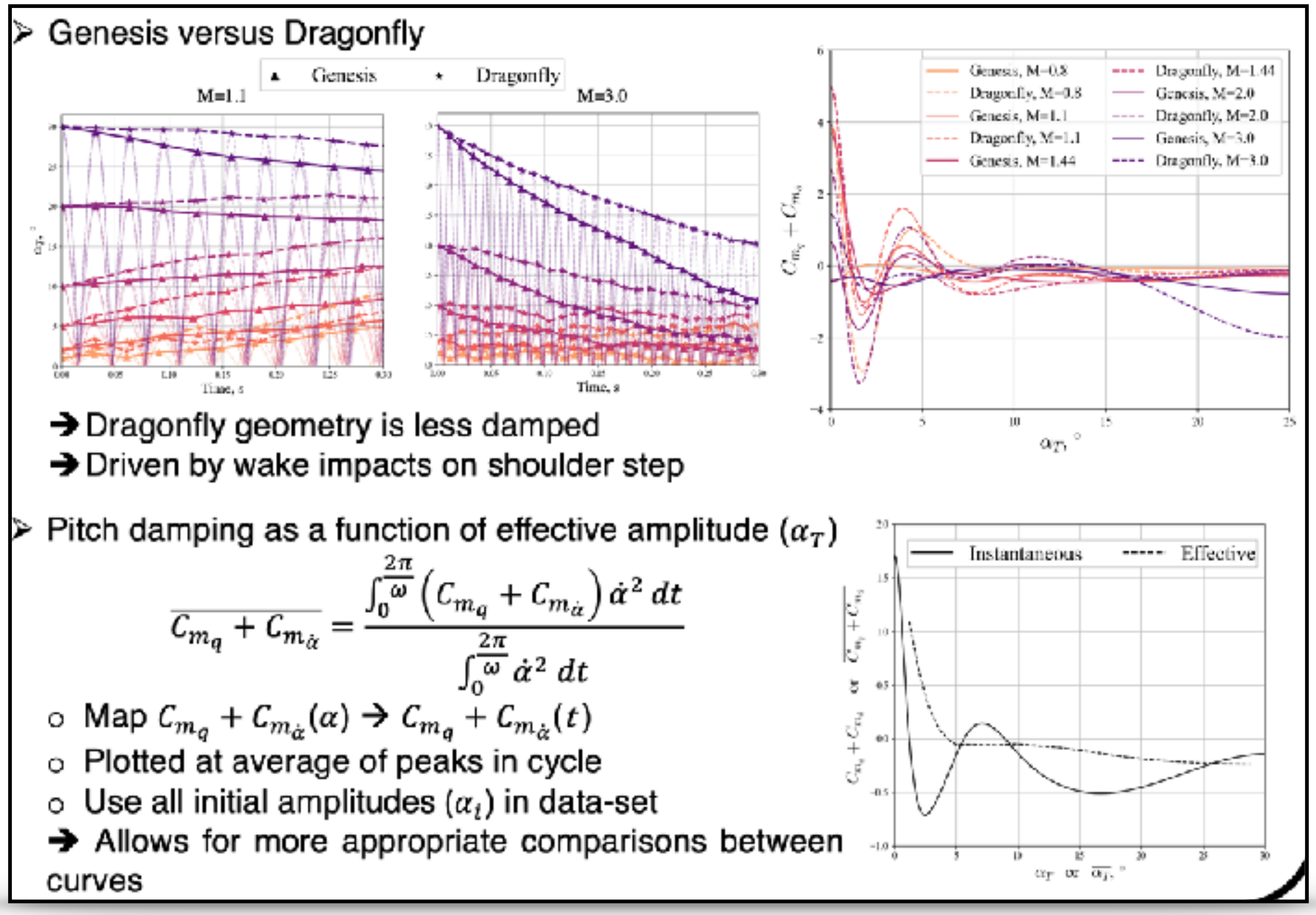
Improved Data Reduction using Inverse Estimation

- Limitations in amplitude based analysis result in poor approximation of $\bar{C}_{m_q}$ curve at small initial angles of attack
  - Sectional fits and aerodynamic models result in flattening of $\bar{C}_{m_q}$ curve near zero where strong growth is observed
- Equations of Motion allow integration of dynamics using existing $\bar{C}_{m_q}$ and C_{m_α} curves
  - Trajectory is propagated and the amplitude and time of each peak in the data set is compared to the raw FFCFD data.
  - Optimizer wrapped around this process yields $\bar{C}_{m_q}$ and C_{m_α} curves which optimally match the entire set of FFCFD data provided
  - "Trained" $\bar{C}_{m_q}$ and C_{m_α} models are validated against previously unseen FFCFD time histories
    - Result is a high fidelity pitch damping sum curve as a function of alpha (instantaneous) that can be directly fed into EoM to use for reconstruction and trajectory estimation based off of FFCFD data



Example reconstruction	Parameter	Density	Mass	Moment of Inertia	Diameter	Area
	Symbol	ρ	m	I	d	S
	Value	1.213	0.633	1.99E-4	6.942	37.8
	Units	kg/m³	kg	kg-m²	cm	cm²

Quincy McKown Poster



Conclusions/Discussion

- FFCFD continues to expand V&V efforts with focus on low supersonic/transonic flow
  - Extensive V&V efforts at moderate to low supersonic cases across a range of vehicle geometries
  - Development of reduced DoF analysis with FFCFD enables faster population of Mach-alpha aero-database for static and dynamic coefficients
  - Orion CM “cross-facility” comparisons show good agreement between simulation predictions and experimental results
- FFCFD support for DragonFly mission under ESM direction
  - Application of end-to-end dynamic stability assessment using 1-DoF simulations have been carried out for a range of Mach numbers and initial AoAs
- Improvement over peak-fitting methodology using machine learning will improve understanding of current limitations and aid in development of future aero-models
  - **GO SEE QUINCY’S POSTER!**

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4. Brock, Joseph M, et al. "Free-Flight CFD Simulations of Transonic MPCV Ballistic Range and Subsonic AA-2 Flight Test". Pending Journal of Spacecraft and Rockets submission

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6. Stern, Eric, et al. "A Method for Deriving Capsule Pitch-Damping Coefficients from Free-Flight CFD Data". Pending Journal of Spacecraft and Rockets submission

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